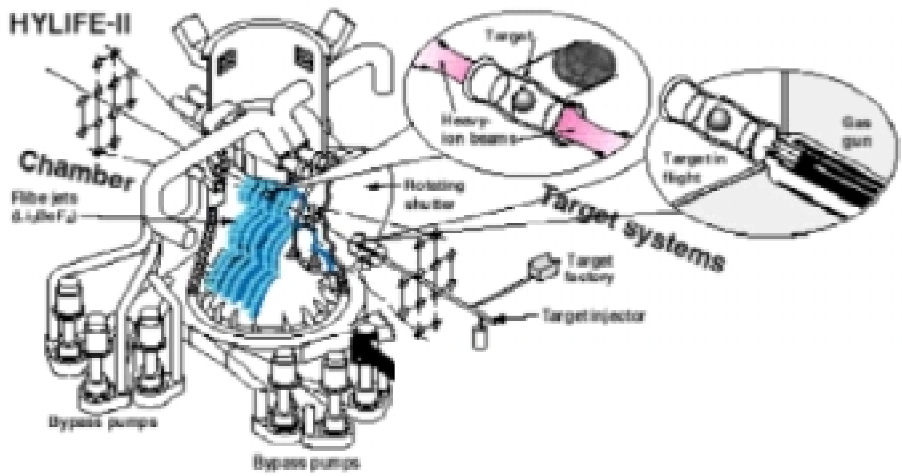
Introduction to Ion Beam Fusion and Target Design for IFE



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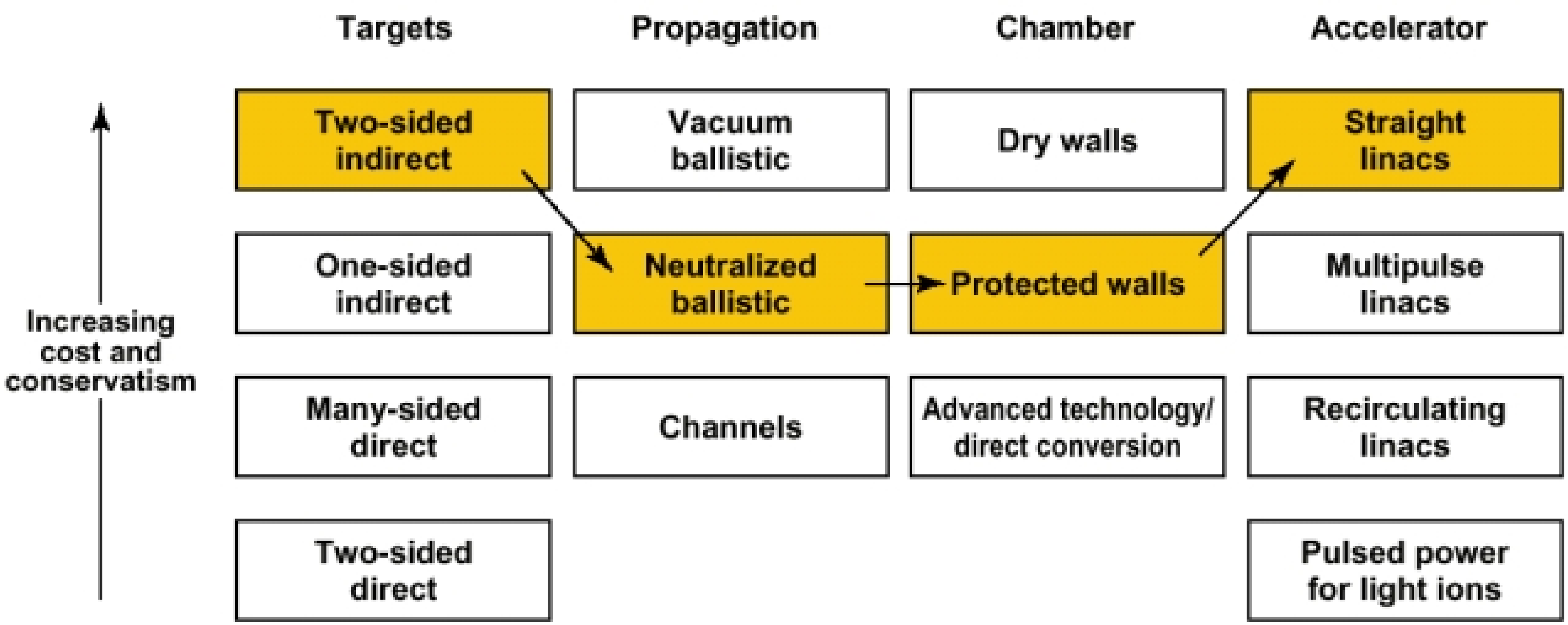
Presented at:

OFES Budget Planning Meeting
Washington, DC

March 13-15, 2001

***This work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.**

The program to develop the science required for ion beam fusion is a coordinated effort utilizing the separability of targets, drivers and chambers to individually optimize subsystems



Targets

- Synergistic with DP program
- Consistent with protected wall chambers
- Hohlraum provides injection shield

Propagation

- Allows focusing of higher current beams → lower cost accelerators

Chamber

- Minimizes materials development
- Reduced size chamber and focal distance

Accelerator

- Flexible architecture suitable for many target types
- Least physics uncertainties

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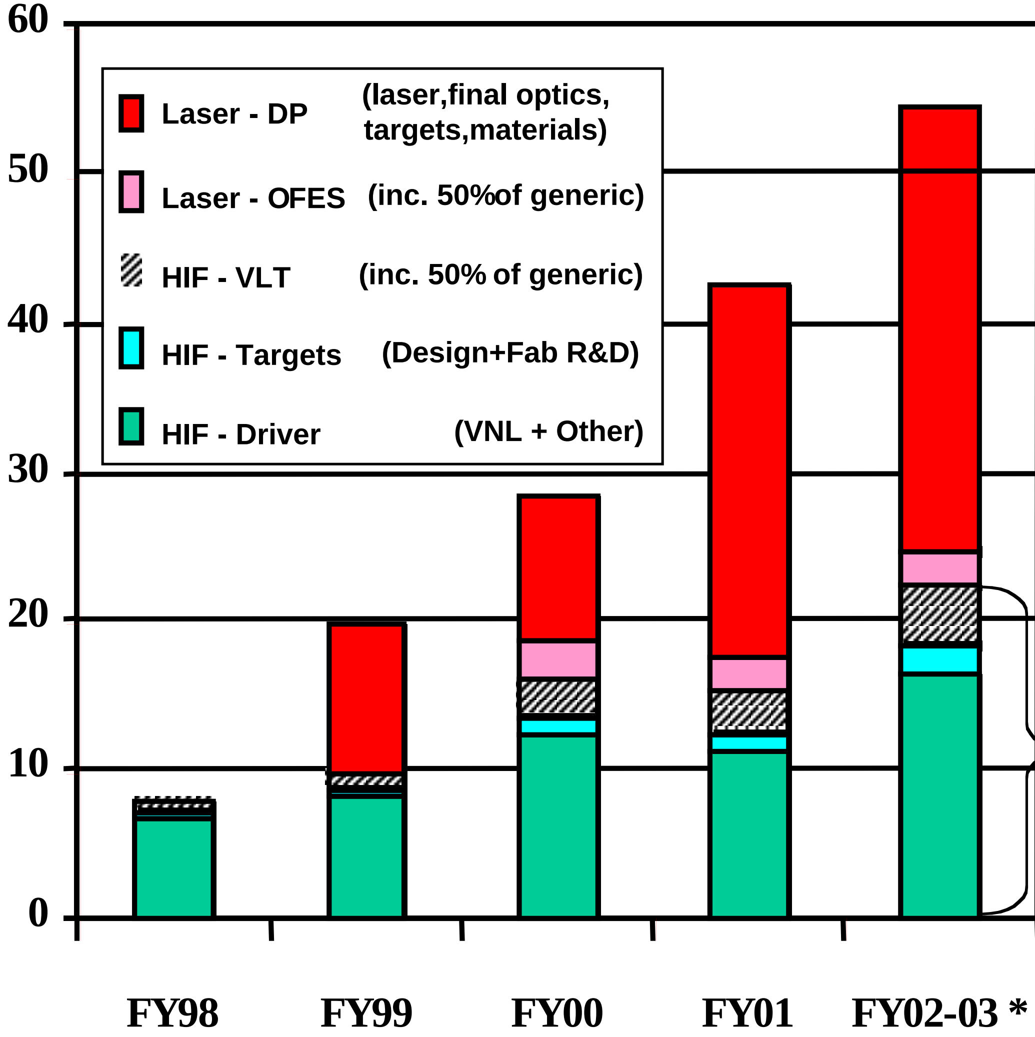
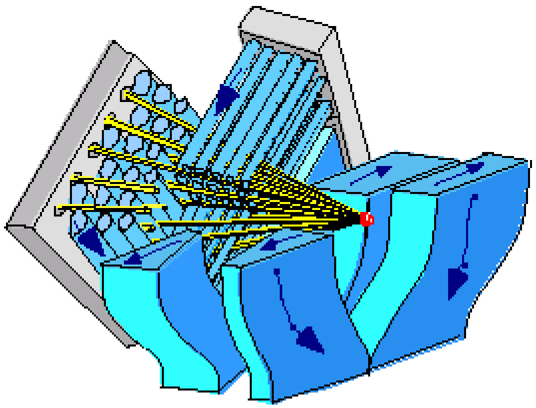
Contrary to expectations from the consensus agreement at Knoxville, FY01 funding for HIF decreased even though combined OFES+DP support for IFE increased



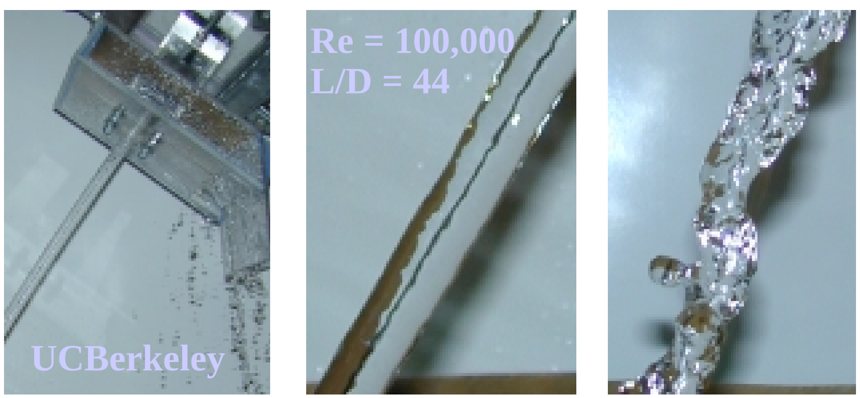
- The relatively modest reductions in funding for (FY01) have had significant effects
  - — We were forced to delay the completion of the new ion source test stand at LLNL
    - - this facility is needed for research on compact, high brightness ion sources
  - — We will complete only 1/4 of the HCX Phase I hardware (10 of 40 quadrupoles) in FY01
    - - each set of 10 costs approximately $300 k. We need about 40 quads to have enough beam plasma periods to be confident of our results
- Loss of staff (3 people relative to the beginning of FY01)

*Assuming a $300M fusion budget, the request funding restores the balance between HI and Laser IFE envisioned at Knoxville

IFE technology community is making excellent progress on science of liquid jets for thick liquid wall chambers



Liquid jets (molten salt Li_2BeF_4) surround target to protect structures from radiation damage and to reduce neutron activation



low-contraction nozzle | w/ conditioning | w/o conditioning

High quality jets in UCB experiment

- **Scaled water experiments accurately replicate hydrodynamic phenomena**
- **Experiments underway at UCB, UCLA, and Georgia Tech**
  - **Low surface ripple jets**
  - **Oscillating jets**
  - **Disruptions simulating fusion energy pulse**
  - **Vaporization & condensation**

Target design addresses critical issues for developing attractive IFE concepts and for understanding HED physics

Target Requirement	IPPA IFE Goal 1 HED Scientific Issue	IPPA IFE Goal 2 Attractiveness of IFE
Power/Energy	Drive Temperature Symmetry Stability	Driver Beam Quality Driver Cost
Pulse shaping/pulse length	Fuel adiabat/EOS	Driver Beam Conditioning
Spot size/Intensity	Drive Temperature Stability Transport/Focusing	Beam focusing and Chamber Design
Beam geometry	Symmetry/Radiation Transport	Chamber Design Wall Protection Approach
Target Material (hohlraum/capsule)	Wall albedo … Coupling Efficiency Capsule Stability	ES&H Manufacturing
Target Specifications	Hydrodynamic Instability Symmetry	Manufacturing

The IFE target design work includes work on the baseline approaches and more speculative advanced targets

- **Heavy Ion Indirect Drive**
  - a) Identify tradeoffs among accelerator energy, power, particle range, focal spot size, intensity, beam geometry
  - b) Optimize target materials for ES&H and manufacturability
  - c) Possible experiments on Omega and Z to test unique features
- **Laser Direct Drive**
  - a) Optimize tradeoff between gain, stability, and imprint for IFE targets using DP ASCI codes
- **Some possible advanced targets**
  - a) Fast ignitor targets with minimal plasma propagation path
  - b) Laser driven targets compatible with liquid wall protection
  - c) Direct drive ion targets

The guidance case budget will result in a reduction in effort on IFE target design

	FY 2001	FY 2002	FY 2003
Staffing (FTE)	3.9	3.73	3.47
Operating Expense ($K)	1080	1080	1080

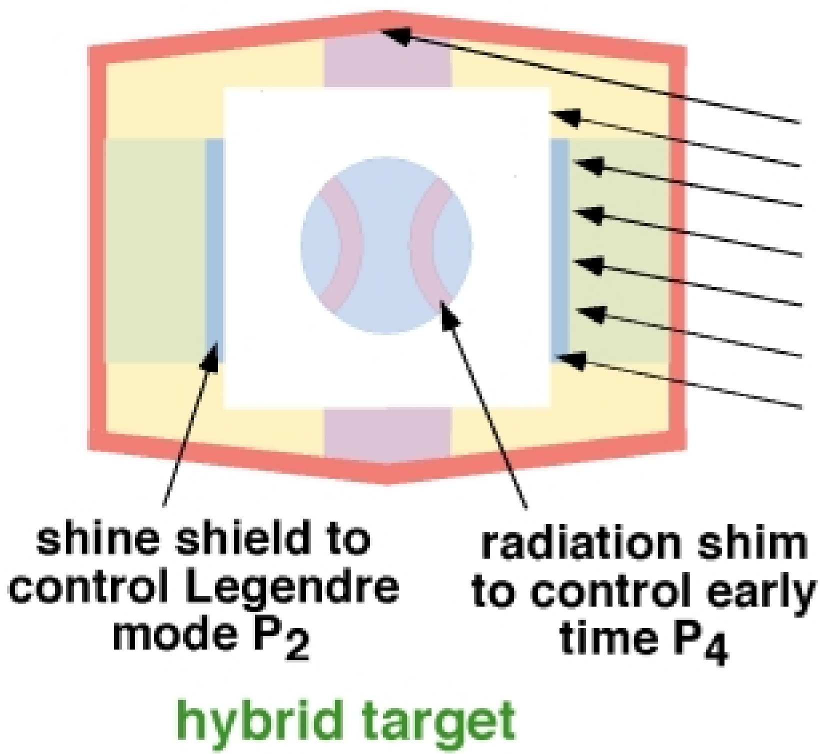
- Under guidance case, further code improvements will be delayed and other design activities including involvement in collaborative experiments on DP and international facilities will be slowed down

The request case budget will allow an expansion in IFE target design consistent with a $50 M/yr IFE Program

	FY 2001	FY 2002	FY 2003
Staffing (FTE)	3.9	6.0	6.0
Operating Expense ($K)	1080	1787	1857

- The increase in effort will be directed toward:
  - a) possible experiments on existing facilities to test unique features of IFE targets in symmetry techniques and target geometry
  - c) exploration of a wider range of target options
  - b) improvements in electron transport

Hybrid targets for HIF use new symmetry control Techniques to accept larger beam spots

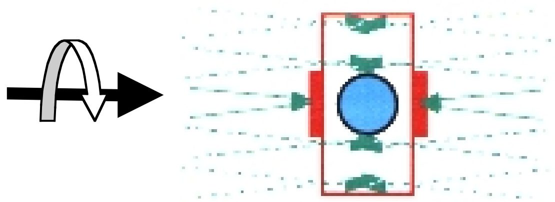


	Hybrid	Distributed radiator
Spot size (mm)	3.8 x 5.4	1.8 x 4.1
Beam energy (MJ)	6.7	5.9
Gain	58	68

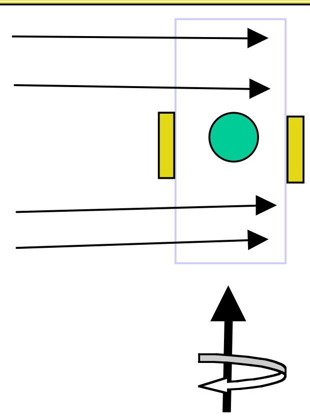
We want to partner with DP to test these techniques because we have needs in common
- **— Z relies on radiation flow, not beam location for symmetry**
- **— NIF needs to control P_4 and Y_{98}**

By using the symmetry control techniques we are developing, we can design hohlraums that accept very large beam spots

Tuna can



Illumination through one side of hohlraum



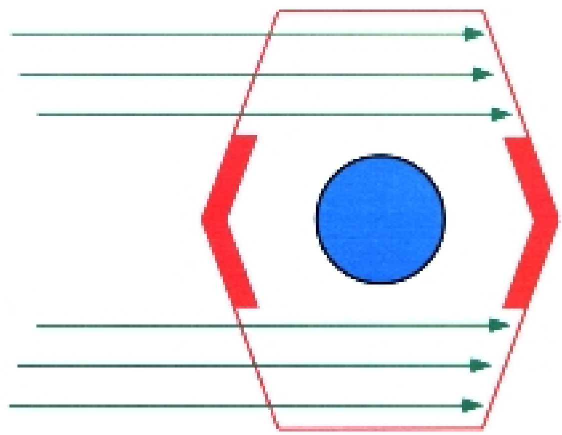
By using a hohlraum shaped like a tuna can instead of a soup can, very large beam spots are possible

Status:
Simple scaling laws predict 7-8 MJ of beam energy with up to a 7 mm spot and gain ~ 50-60

Spot size ~ 5 mm
Baseline spot ~ 1.7 mm

- 3-D geometry can be calculated with ASCI codes which have been modified to include ion beam deposition

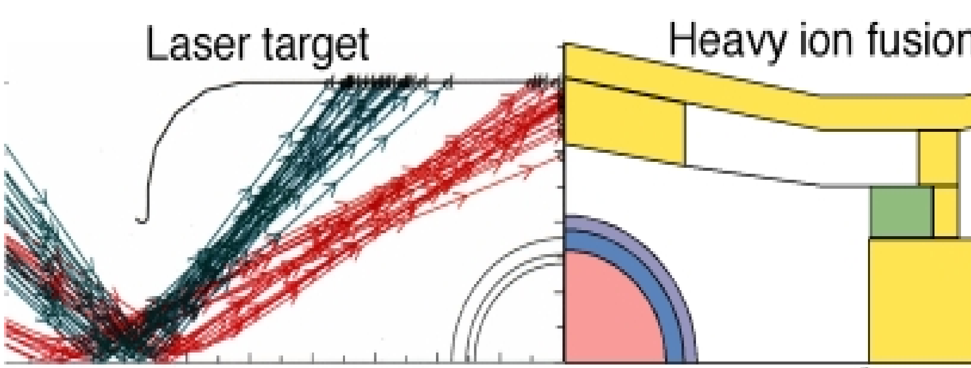
Irradiation from the hohlraum side could result in a 1-sided irradiation geometry and significant increase in spot size



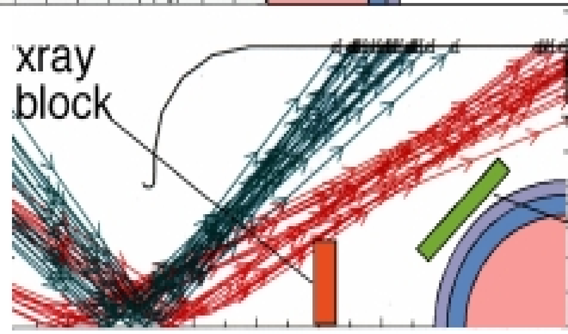
Spot size ~ 5 mm
Baseline spot ~ 1.7 mm

- **3-D geometry can be calculated with ASCI codes which have been modified to include ion beam deposition**

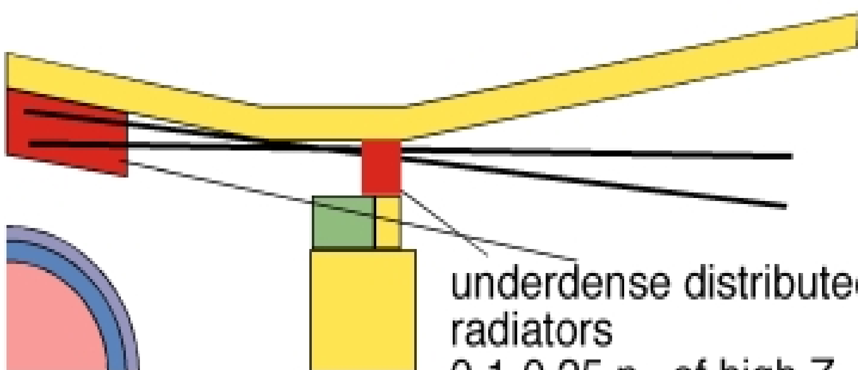
Design ideas from HIF may lead to more attractive indirect drive laser IFE targets



HIF uses larger capsule in somewhat smaller hohlraum

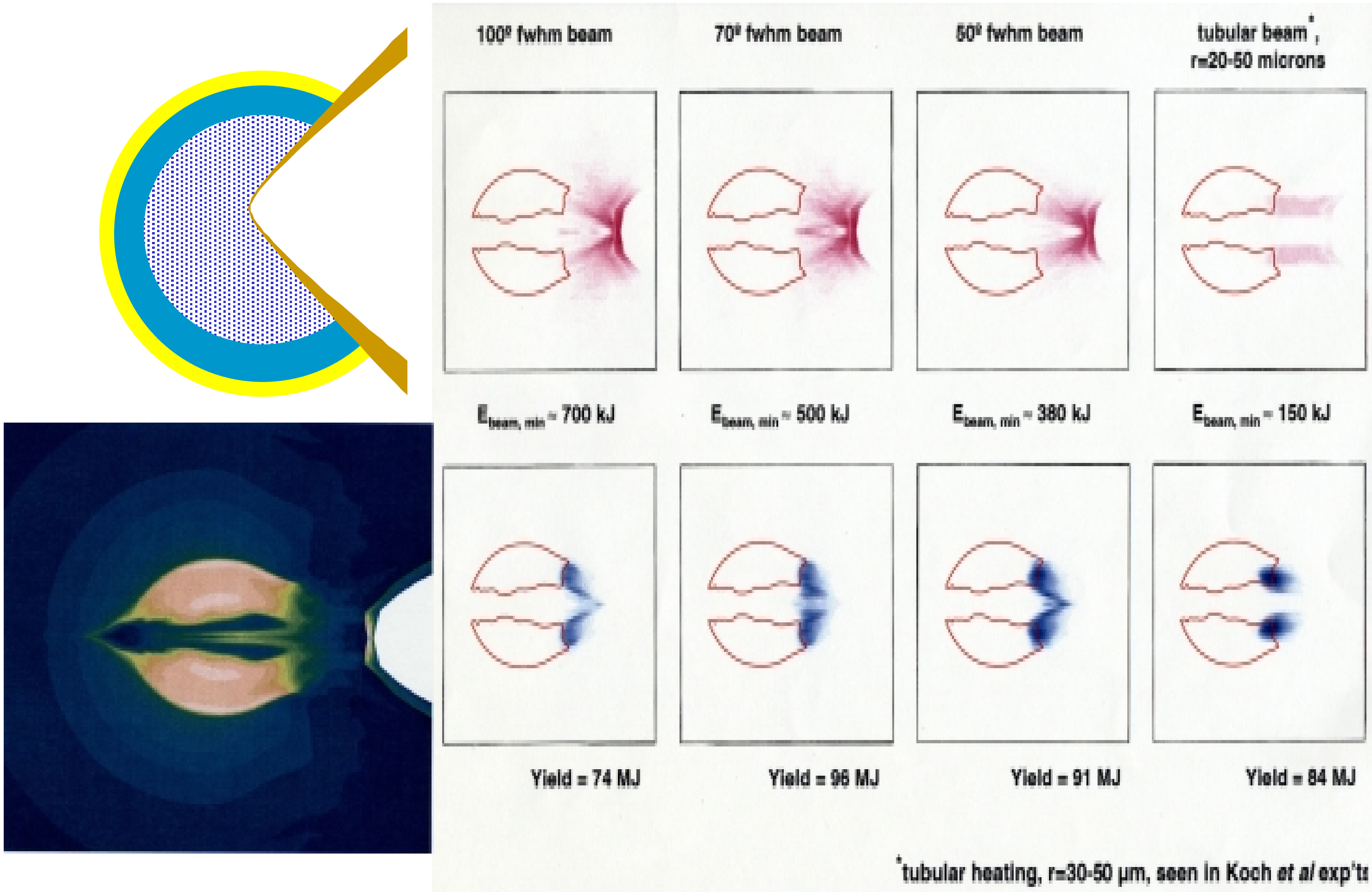


Laser targets might be able to improve coupling and symmetry with blocks and burnthroughs



HIF style focussing might allow a very tight bundle of laser beams consistent with HYLIFE and distant final optics

Cone focus designs allow access to compressed fuel fast ignition



Promising designs led to National Laser User Facility shot allocation for summer 2001

The fast ignition project is a new ‘concept exploration’ funded at ~ $760 K/yr

- Energy transport is the key area of uncertainty and the focus of the OFES project

- Project is collaborative in US between Universities and labs LLNL, GA, Princeton, UC Davis, UC San Diego
  - — 4 good students from U.C. Davis

- International collaborations are the major basis of the experimental work (Laser facilities in Japan/France/UK)
  - — Laser facility time is “free” to collaboration, but worth ~ $1.5M this year

FI research has a high scientific interest and international progress is rapid

- FI research is linked to intense scientific interest in relativistic laser matter interactions (e.g. 14 PRL in months to Feb. 2000)
- A milestone result from Japan last year demonstrated laser generated relativistic electron heating of an implosion with 10% energy transfer efficiency

A jointly funded center of excellence is a future possibility

- Defense Programs is examining options to use PW class lasers
- NSF supports ultra-high intensity research and also NSF centers
- NASA is interested in laboratory astrophysics with lasers
- The NRC Fusion Review recommended creating centers of excellence in fields of high scientific interest with strong cross linkages
- A multi-agency center of excellence based on PW laser is a possibility

Backups

Scaling provides basis for replicating IFE thick-liquid chamber phenomena using water jets

Mass and momentum conservation

$$\nabla \cdot \mathbf{v} = 0 \qquad \rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v}\right) = -\nabla p + \mu \nabla^2 \mathbf{v} + \rho \mathbf{g}$$

Free surface pressure boundary condition with impulse load I

$$p - p_v = \sigma\left(\frac{1}{r_1} + \frac{1}{r_2}\right) \qquad \text{where} \qquad p_{v,ave} = \frac{IU}{L} = \frac{U}{L}\int_0^{L/U} p_v \, dt$$

Nondimensionalize with appropriate scaling parameters:

$$\mathbf{v}^* = \mathbf{v}/U \qquad \nabla^* = L\nabla \qquad p^* = p/\rho U^2 \qquad t^* = ft \qquad r^* = r/L \qquad p_v^* = \frac{p_v L}{IU}$$

Giving governing equations:

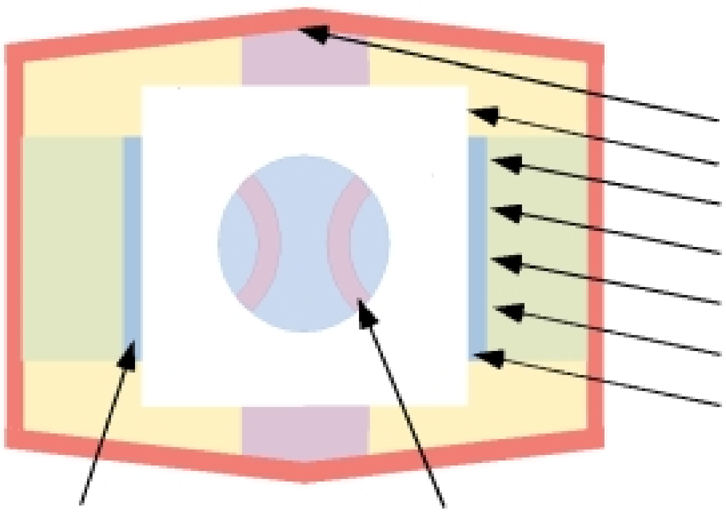
$$\nabla^* \cdot \mathbf{v}^* = 0 \qquad \mathrm{St}\frac{\partial \mathbf{v}^*}{\partial t^*} + \mathbf{v}^* \cdot \nabla^* \mathbf{v}^* = -\nabla^* p^* + \frac{1}{\mathrm{Re}}\nabla^{*2}\mathbf{v}^* + \frac{1}{\mathrm{Fr}}\frac{\mathbf{g}}{g}$$

$$p^* - I^* p_v^* = \frac{1}{\mathrm{We}}\left(\frac{1}{r_1^*} + \frac{1}{r_2^*}\right)$$

A scaled system behaves identically if initial conditions and St, Re, Fr, I*, and We are matched...

Important simplifications:
No EOS, No energy equation
No MHD

We have developed symmetry control techniques for distributed radiator targets for heavy ion fusion

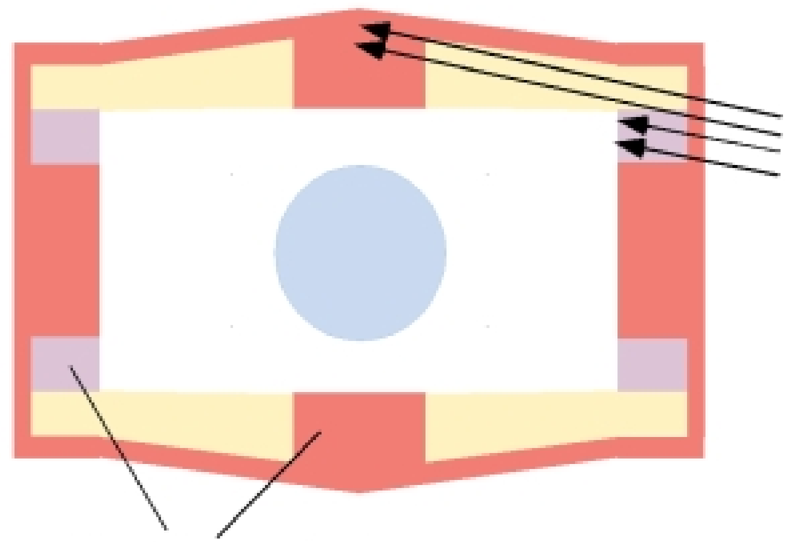


shine shield to control Legendre mode P_2

radiation shim to control early time P_4

hybrid target

Beam spot: 3.8 mm x 5.4 mm
Effective radius: 4.5 mm
6.7 MJ beam energy
Gain = 58



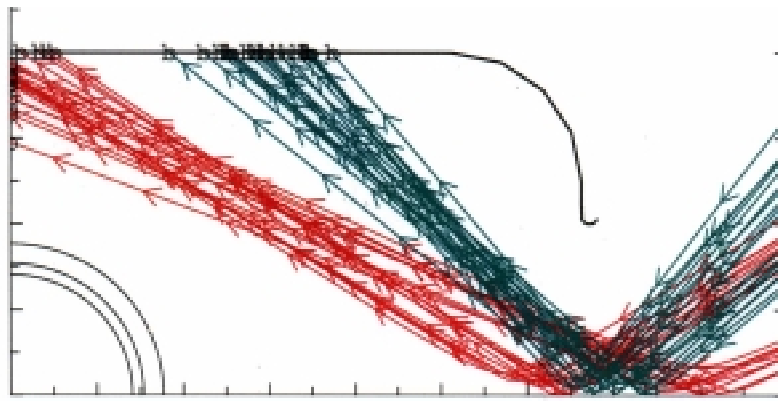
Pressure balance holds position of radiators

distributed radiator target

Beam spot: 1.8 mm x 4.1 mm
Effective radius: 2.7 mm
5.9 MJ beam energy
Gain = 68

66% increase in beam radius with a 14% increase in beam energy

Recent advances in design for targets indirectly driven by lasers have reopened this option for IFE



Peak laser power 300 TW

Laser energy ~ 2.3 MJ

$E_{capsule}$ ~ 600 kJ

Yield 175 MJ in good symmetry limit

Gain ~ 75

Increased hohlraum coupling efficiency is combination of many small effects

Source	CE(%)
Point design	11
250 eV 7 ns	13
LEH*0.8	15
Cocktail wall	17
Cocktail + LEH	20
CE ~ 90% not 80%	22
A_{can}/A_{case}	26

We are learning to optimize gain in the presence of instabilities

New marginal ignition model:

$E_{ign}(kJ) \sim \alpha^{1.88} V^{-5.89} P^{-0.77}$

Implosion model:

$V \sim \alpha^{0.6} (R/\Delta R) T_R^{0.9}$

Instability growth model:

$N_{efold} \sim (L/(1+0.2\, L\Delta R/R))^{0.5} - 0.8L\, \Delta R/R$

Haan multimode saturation model

Pressure

$P \sim T_R^{3.5}$

Together:

Growth_factor=

Growth_factor(E_{ign}, α, T_R)

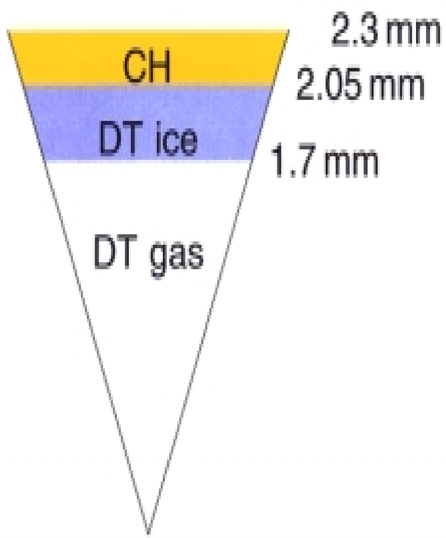
How much higher should V be to overcome predicted mix?

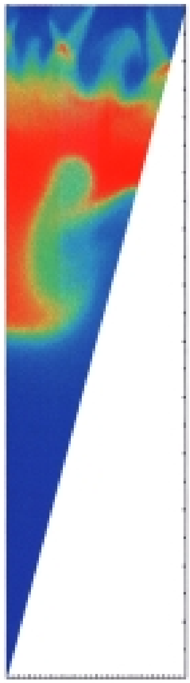
Need multimode burn calculations to check

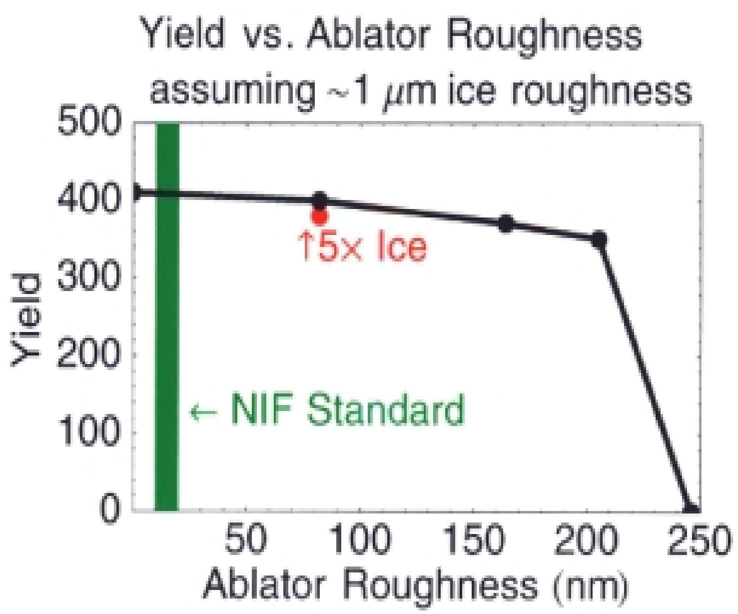
Multimode calculations show a reactor-scale plastic ablator capsule driven at 260 eV is robust enough to handle current estimates of surface roughness

CH capsules more amenable to mass production than Be

Less time to diffusion-fill with DT-> lower tritium inventory



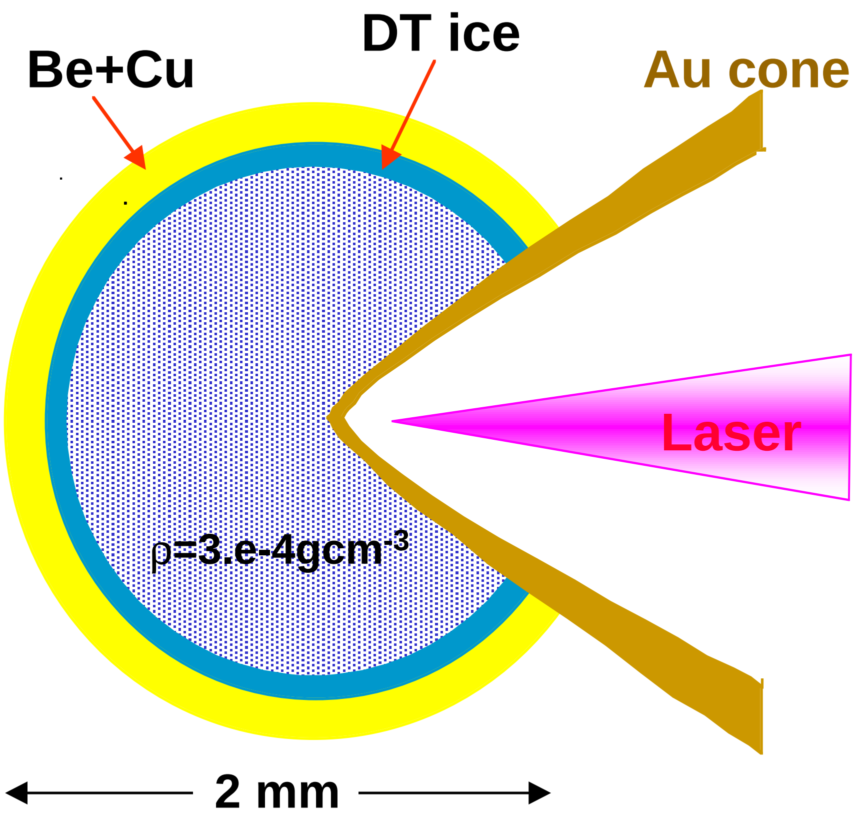




Robustness might be used to relax target fabrication and driver requirements

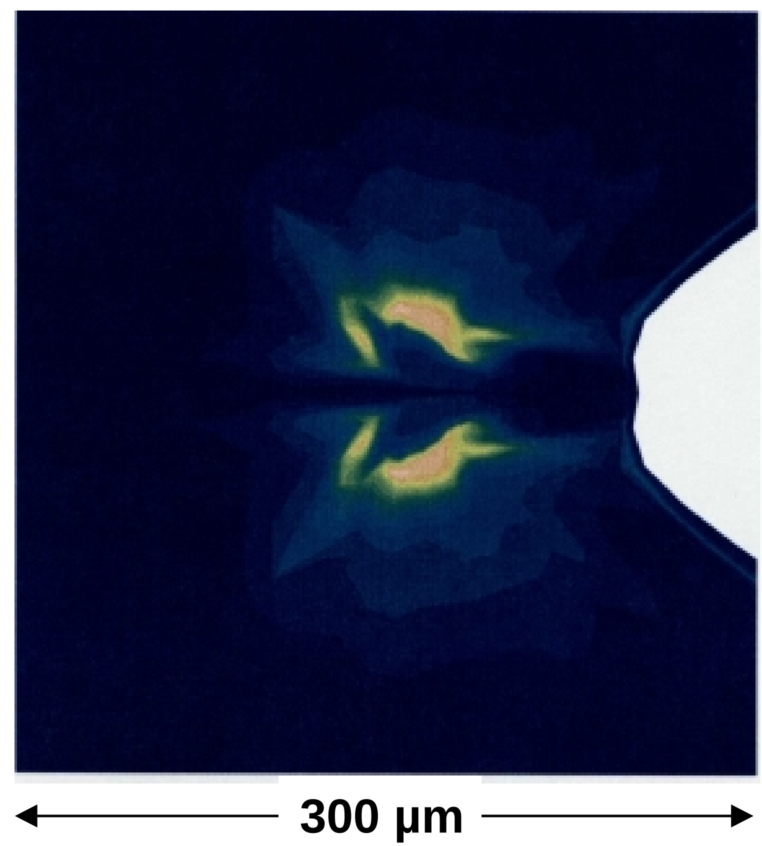
Creative design gives better access to the dense fuel for the ignitor beam in Lasnex design

270eV hohlraum drive



Design will be tested at Omega (NLUF)

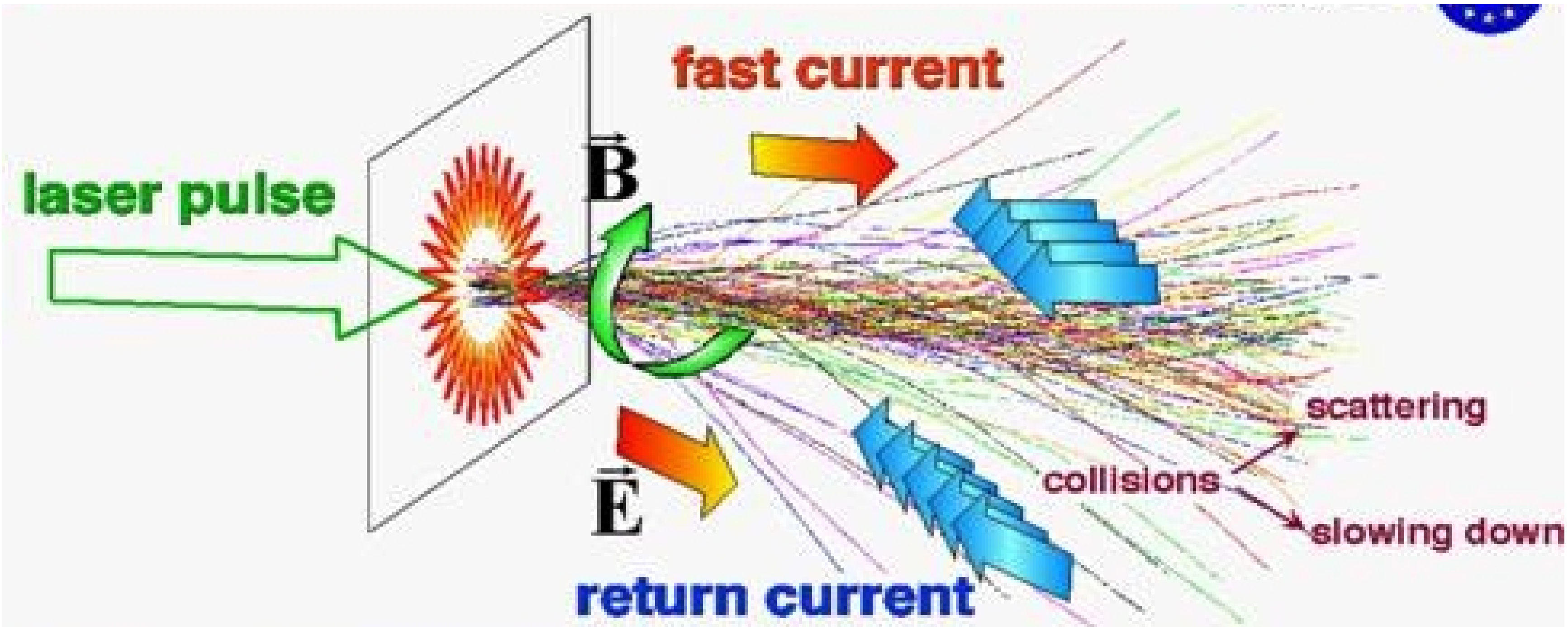
Map of imploded fuel density



$<\rho R>_{DT}=1.33\ g\ cm^{-2}$

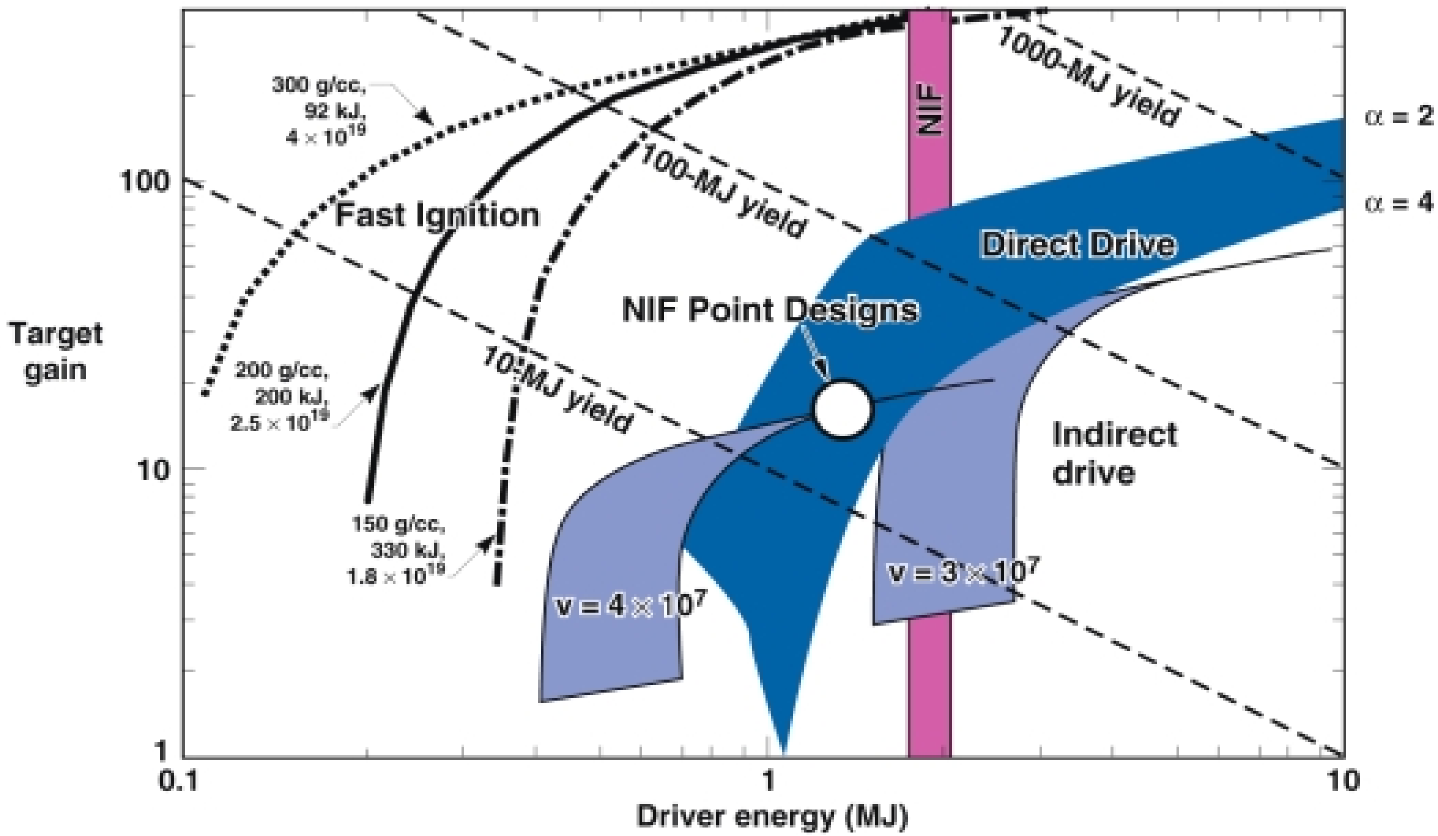
Physics of relativistic interaction and electron transport govern heating by MeV electrons

Hybrid PIC model (Paris) - L Gremillet et.al. France



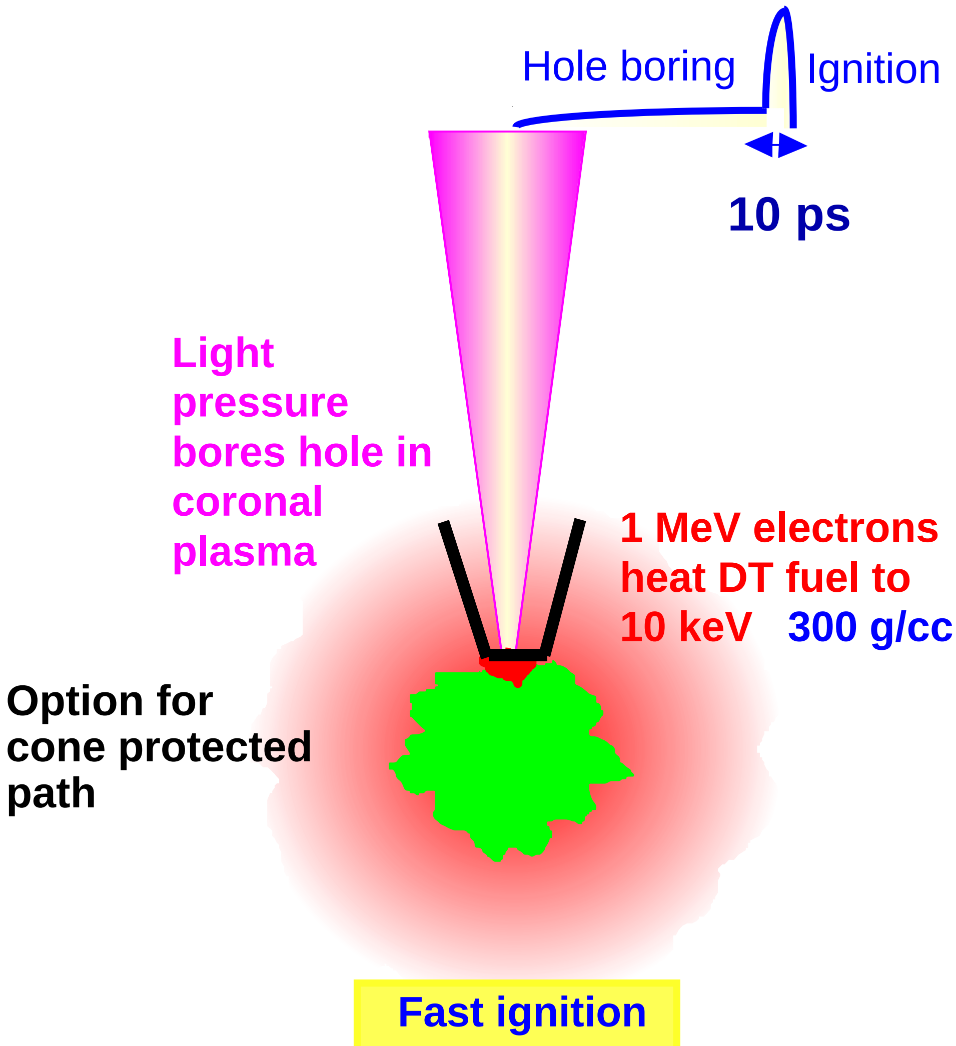
Beam evolves to a net current < Alfven limit with strong magnetic guiding

Fast ignition gives more gain and lower threshold energy than indirect or direct drive



FI model has 8% efficient fuel compression at α=2 and ignitor beam with 30% to electrons and 66% transport to spark

Fast ignition has important advantages for IFE



- **Higher gain allows use of lower efficiency laser drivers**
- **Reduced drive pressure and symmetry allows simpler driver beam geometries**

  -advantage for reactor chamber